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# Comparison of Teleradiometric and Sensitometric Techniques for Visibility Measurements

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# COMPARISON OF TELERADIOMETRIC AND SENSITOMETRIC TECHNIQUES FOR VISIBILITY MEASUREMENTS

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**Abstract**—Visibility measurements of power plant and smelter plumes were conducted as part of the 1981 VISTTA field programs by means of sensitometry of color photographic slides and teleradiometry. The results obtained for 10 sets of measurements with these two techniques at three wavelengths (450, 550 and 630 nm) were compared and showed good agreement for plume sky radiance ratios, with correlation coefficients on the order of 0.9 and average absolute differences of 2–4 per cent. The uncertainty in the plume sky radiance ratio is about 4 per cent for sensitometry. Although this value is slightly higher than the uncertainty of 2 per cent previously reported for teleradiometry (Bergstrom *et al.*, 1982), sensitometry offers the advantage of an instantaneous measurement. In contrast, a manual teleradiometer scan takes on the order of 15 min, and plume visual effects can show large variations in this short time period.

## 1. INTRODUCTION

The study of the impact of power plant and smelter plumes on atmospheric visibility was the subject of several field programs conducted in 1979 and 1981 as part of the EPA-sponsored VISTTA project (Blumenthal *et al.*, 1981). Quantitative measurements of the plume visual effects were conducted during these field programs by means of teleradiometers operated manually, and experimental results were reported for the 1979 VISTTA field programs by Bergstrom *et al.* (1981). These measurements were documented by color photographic slides. Since photographic slides can be digitized and subsequently used to provide quantitative information regarding the contrast of atmospheric plumes at several wavelengths, it is of particular interest to compare measurements obtained by teleradiometry with those obtained from digitized photographic slides, i.e. by sensitometry. If sensitometry offers a measurement accuracy comparable to that of teleradiometry for the quantitative evaluation of plume visibility, it will be most useful in monitoring plume visual effects since photographic measurements can more easily be conducted on a routine basis.

Teleradiometric and sensitometric measurements should have high correlation under well-controlled conditions. However, it is important to evaluate the differences that actually exist when these two techniques are used in the field under conditions that are typical of ambient monitoring of plume visibility.

An evaluation of visibility data obtained with digitized color photographic slides was performed by Henry *et al.* (1981) in a study involving sky–mountain contrast measurements. The results showed that the contrast accuracy obtained with the color photographic slides is on the order of 10 per cent. For a target sky contrast value of −0.2, this is equivalent to an uncertainty in the target sky radiance ratio of 2 per cent. This value is commensurate with that of teleradiometric measurements, which has been estimated to be on the order of 2 per cent for target/sky radiance ratio in comparing side-by-side teleradiometric measurements (Bergstrom *et al.*, 1982).

In this study, we present a comparison of teleradiometric and sensitometric measurements of plume visibility that were conducted during the 1981 VISTTA field programs. Section 2 presents the two measurement techniques, i.e. field measurements conducted with teleradiometers and sensitometric analysis of the photographic slides. Section 3 presents an analysis and discussion of the results. Section 4 provides the conclusions of this study and recommendations regarding the use of monitoring techniques for plume visibility measurements.

## 2. DESCRIPTION OF THE MEASUREMENT TECHNIQUES

### *Teleradiometric measurements*

The teleradiometric measurements were conducted by means of a Meteorology Research, Inc. (MRI) Model 1030 instrument. A teleradiometer consists of a telescope objective lens that focuses the radiance from a distant object on a photodiode. Measurements can be performed at four different wavelengths by means of four narrow-band interference filters. The effective band-centers of these filters are at 405, 450, 550 and 630 nm. Absolute measurements of sky and object radiances are determined by calibrating the instrument with a standard light source. The procedure for teleradiometer calibration was reported by Bergstrom *et al.* (1982). In evaluating plume visual effects, it is most important to measure plume contrast against the sky, or the ratio of plume radiance at 450 and 630 nm (blue/red ratio). Thus, only relative radiometric measurements are used, and the absolute values of the measured radiances are not required.

The field measurements were conducted as follows: the teleradiometer was aimed at a point in the sky below the

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plume that was to be measured, and measurements were taken at each of the four wavelengths. The elevation angle was then incrementally changed, and measurements were taken at the four wavelengths for each elevation angle. Thus, the teleradiometer performed a vertical scan of the sky, or plume radiance, from below to above the plume. Performance of a set of teleradiometric measurements required about 15 mins for a well-defined plume.

The results were plotted for each wavelength as a function of the elevation angle, and interpolated between data points by means of a computer program. For example, Fig. 1 shows measurements of a power plant plume taken on 20 February 1981 with the green filter, i.e. at 550 nm. The visual effect of the plume appears as a decrease in radiance for a dark plume (for a bright plume there would be an increase in radiance). The plume contrast at a given wavelength is calculated at the maximum (bright plume) or minimum (dark plume) point in the section of the radiance curve that corresponds to the plume. The radiance of the plume is taken as the measured radiance value at that point. The radiance of the sky that corresponds to the case in which no plume is present is obtained by interpolation between sky radiances below and above the plume. For example, in Fig. 1, the measured plume radiance is 11.22 $\mu$W cm$^{-2}$ sr$^{-1}$ nm$^{-1}$, and the sky radiance at the same elevation angle is estimated by interpolation to be 13.17 $\mu$W cm$^{-2}$ sr$^{-1}$ nm$^{-1}$; this leads to a plume sky radiance ratio of 0.85 at the wavelength 550 nm.

*Sensitometric measurements*

Color slide photographs of the plume were taken with Kodachrome 64 film at the beginning and at the end of each set of teleradiometric measurements. The teleradiometer appeared at the bottom of the photograph so that it was possible to locate on the photograph the part of the plume that had been measured by the teleradiometer. The color slide photographs were subsequently digitized using a microdensitometer to provide quantitative measurements of the light intensity recorded on the photograph. This measurement technique is called sensitometry.

The sensitometric measurements were conducted at Perkin-Elmer in Garden Grove, California. The section of the photograph to be digitized corresponded to the imaginary vertical line across the plume that was scanned by the teleradiometer. Since there was some uncertainty regarding the exact location of that scan, three digital scans, 35 $\mu$m apart horizontally, were performed on the slide. The aperture used in the digitization process was 35 $\mu$m square. Smaller resolution, though possible, would result in a lower response of the photographic film; thus, the 35-$\mu$m square aperture appeared to be the most appropriate (Eastman Kodak Company, 1974). This aperture corresponds to a vertical subtending angle of view of 0.039°, which is similar to the 0.035° angle of view of the teleradiometer.

The slide digitization was conducted at three wavelengths using narrow-band filters (Kodak Wratten filters numbers 92 [red], 93 [green] and 94 [blue]). Filter transmittance is above 0.1 percent between 420 and 500 nm (blue filter), 515 and 590 nm (green filter) and above 620 nm (red filter). Peak filter transmittance occurs at 450 nm (blue filter), 540 nm (green filter) and above 700 nm (red filter) (Eastman Kodak Company, 1976). The maximum sensitivities of the three layers of Kodachrome 64 film are at 430 nm (yellow-forming layer), 550 nm (magenta-forming layer), and 650 nm (cyan-forming layer) (Eastman Kodak Company, 1974).

An example of a series of slide-digitization scans using a green filter is shown in Fig. 2 for the 20 February 1981 case study. The optical density of the picture elements (pixels) is

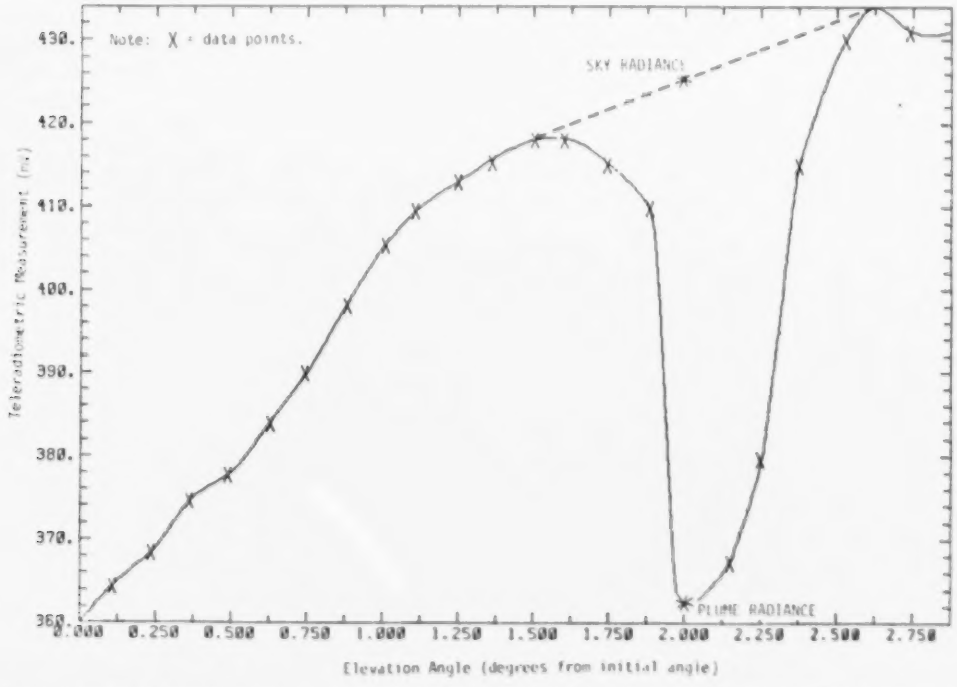


Fig. 1. Example of teleradiometric measurement (green filter). Kincaid power plant plume, 1125–1145 CST, 20 February 1981. The radiance is measured in mV by the teleradiometer. From the teleradiometer calibration 1 mV = 0.0310 $\mu$W cm$^{-2}$ sr$^{-1}$ nm$^{-1}$.

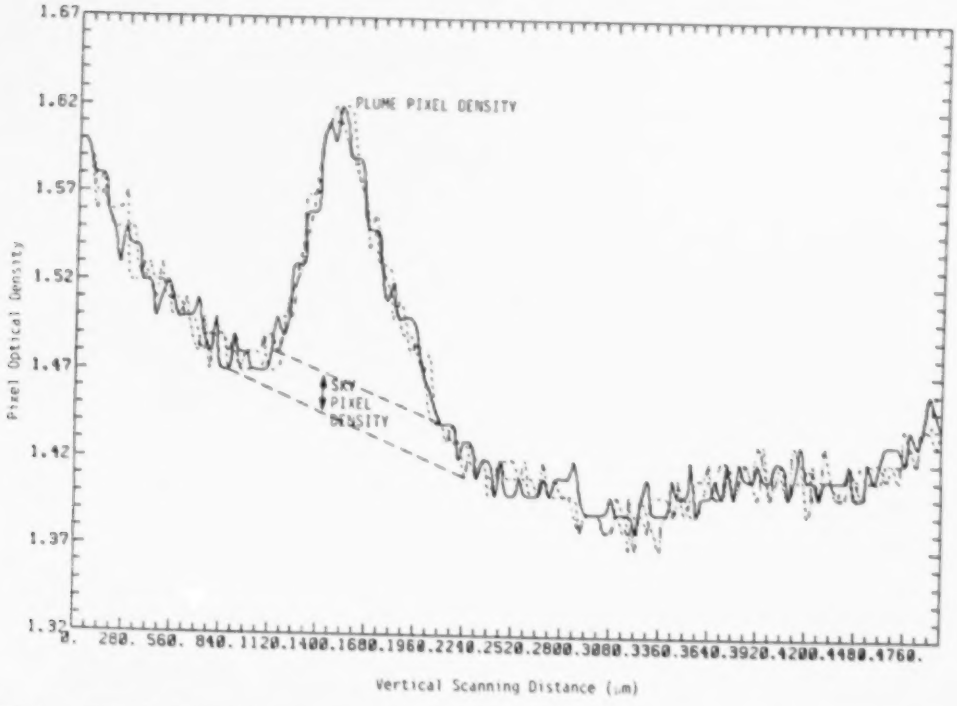


Fig. 2. Example of sensitometric measurement (green filter). Kincaid power plant plume, 1145 CST, 20 February 1981.

plotted as a function of the vertical distance on the photographic slides for each of the three digital scans. These scans are equivalent to the vertical teleradiometer scan that was presented in Fig. 1. It may be noted, however, that a higher density corresponds to a lower exposure so that a dark plume appears in a sensitometric plot as an increase in pixel density, whereas a bright plume appears as a decrease in pixel density.

The pixel density of the plume was defined as the value of the maximum (dark plume) or minimum (bright plume) of the plume section of the curves. The pixel density of the background sky at the same location was determined by interpolation between the sky density values below and above the plume. Upper and lower bounds could be determined for these values since pixel densities were available for three scans.

The density of the pixels measured by the slide-digitization technique had to be converted into a quantity linearly related to the radiance that was recorded on the photographic slide. This conversion was achieved by using characteristic curves that relate the slide density to the original exposure for a given wavelength and exposure conditions. Standard characteristic curves are provided by Eastman Kodak Company (1974). However, it appears that the characteristic curves vary slightly from film to film and from one series of photographs to another because of different film pigment and exposure conditions.

Therefore, it appeared to be more accurate to construct characteristic curves specific to the photographs being analyzed. This was done as follows: prior to photographic measurement of the plume, a reference gray scale placed perpendicular to the direct solar beam was photographed. Since reflectances of the gray scale were known Macbeth (1981), it was possible to construct a characteristic curve representing the pixel density as a function of a normalized exposure that was proportional to the gray scale reflectances. The use of a normalized exposure was suitable for this study because the sensitometric measurements are relative, that is, one measures the ratio of two radiances or a contrast. An example of the characteristic curves constructed for the 20 February 1981 case study is shown in Fig. 3. Differences between plume/sky radiance ratios calculated with characteristic curves constructed from a reference gray scale and radiance ratios calculated with standard characteristic curves (Eastman Kodak Company, 1974) ranged from 0 to 2 per cent.

The pixel densities obtained from sensitometric curves such as those in Fig. 2 were then converted to normalized exposures by means of the characteristic curves. For example, for the 20 February 1981 case study, at 540 nm, the maximum plume pixel density was between 1.61 and 1.62 and the corresponding sky pixel density was between 1.465 and 1.44. These values correspond to normalized exposures of 0.303 and 0.300 for the plume, 0.340 and 0.353 for the sky, and plume/sky radiance ratios of 0.89 and 0.85. The plume/sky radiance ratio is thus defined as the average of these upper and lower bounds, with an uncertainty that includes these bounds, i.e. $0.87 \pm 0.02$.

## 3. PLUME VISIBILITY MEASUREMENTS

In this section, we present a comparison of teleradiometric and sensitometric measurements conducted during the 1981 VISTTA field programs. We briefly describe the field programs and then discuss the visibility measurement results.

### *Description of the field programs*

The 1981 VISTTA field programs consisted of two studies that were conducted in February 1981 and in

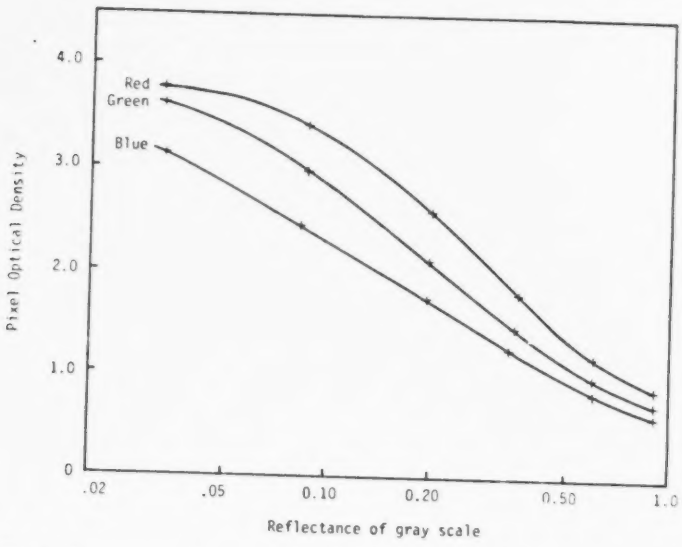


Fig. 3. Characteristic curves constructed from sensitometric measurements of a reference gray scale, 1115 CST, 20 February 1981.

August and September 1981. One of the major objectives of the VISTTA project was to obtain quantitative information related to the visual effects of power plant and smelter plumes. To this end, teleradiometric measurements and photographs of the plume studies were taken by Systems Applications, Inc. and Meteorology Research, Inc.

The objective of the February 1981 VISTTA field program was to study the contribution of a coal-fired power plant to visibility impairment in a winter midwestern environment. Plume visibility measurements were performed during the period of 12–26 February 1981 in the vicinity of the Kincaid power plant near Springfield, Illinois.

The objective of the August–September 1981 VISTTA field program was to study visibility impairment due to emissions from a coal-fired power plant in a midwestern summer environment and from copper smelters in a southwestern summer environment. Plume visibility measurements were conducted from 21 to 29 August 1981 in the vicinity of the Labadie power plant near St. Louis, Missouri, and from 6 to 9 September 1981 in the vicinity of the Magma copper smelter near San Manuel, Arizona, and the Phelphs–Dodge copper smelter near Douglas, Arizona.

*Analysis of the results*

Visibility measurements that corresponded to fairly well-defined plumes were selected for this analysis. Because dispersive atmospheric conditions made it difficult to measure the Kincaid power plant plume, only three case studies were identified. These cases were characterized by clear background skies and a visual range of 120–205 km. Measurements in the vicinity of the Labadie power plant were limited by the low visual range, on the order of 40 km; thus, only two sets of reliable measurements were obtained. The measurements of 24 August were taken against a clear background sky, whereas those of 29 August were taken against a gray, uniformly cloudy background. The best measurements of the smelter plumes were obtained on 8 September for the San Manuel smelter plume. Five sets of measurements were performed with clear background skies and a visual range of 170 to 220 km.

Two cases (24 February and 29 August) show forward scattering conditions with scattering angles of 40 and 50°, respectively. The 24 February case characterizes a bright plume against a clear background sky, whereas the 29 August case shows a dark plume against a cloudy background sky. Other case studies are for backward scattering conditions with scattering angles ranging from 90 to 140°, and show dark plumes against clear background skies. The distances at which the plumes were observed range from 7 to 34 km, and the distances between the plume and the observer range from 3 to 14 km. A detailed description of these case studies is given by Seigneur *et al.* (1983). Table 1 presents the teleradiometric and sensitometric results of the 10 case studies that were analyzed. Teleradiometric measurements were conducted by Systems Applications, Inc. for 7 case studies, and the measurements for the last 3 case studies of 8 September 1981 were conducted by Meteorology Research, Inc. Characteristic curves were constructed from gray scale reference photographs for the first 7 case studies. Because no gray scale photographs were available for the last 3 case studies, standard characteristic curves were used (Eastman Kodak Company, 1974). In general, a photograph was taken at the beginning of

Table 1. Comparison of teleradiometric and sensitometric measurements of plume/sky radiance ratio

| Time and location of measurement | Blue range | | Green range | | Red range | |
|---|---|---|---|---|---|---|
| | Teleradiometry | Sensitometry | Teleradiometry | Sensitometry | Teleradiometry | Sensitometry |
| 1125–1145 CST, 02-20-81 Kincaid power plant | 0.86 ± 0.02 | 0.79 ± 0.04<br>0.86 ± 0.03 | 0.85 ± 0.02 | 0.82 ± 0.04<br>0.87 ± 0.02 | 0.90 ± 0.02 | 0.88 ± 0.04<br>0.90 ± 0.03 |
| 0740–0848 CST, 02-24-81 Kincaid power plant | 1.04 ± 0.02 | 1.15 ± 0.04<br>1.07 ± 0.04<br>1.04 ± 0.04 | 1.13 ± 0.02 | 1.16 ± 0.02<br>1.08 ± 0.03<br>1.07 ± 0.02 | 1.15 ± 0.02 | 1.15 ± 0.04<br>1.11 ± 0.02<br>1.15 ± 0.03 |
| 0704–0739 CST, 02-25-80 Kincaid power plant | 0.89 ± 0.02 | 0.94 ± 0.03<br>0.93 ± 0.03 | 0.93 ± 0.02 | 0.96 ± 0.02<br>0.95 ± 0.02 | 0.96 ± 0.02 | 0.98 ± 0.02<br>0.96 ± 0.01 |
| 1828–1848 CST, 08-24-81 Labadie power plant | 0.94 ± 0.02 | 0.90 ± 0.05<br>1.00 ± 0.05 | 0.99 ± 0.02 | 1.00 ± 0.05<br>1.00 ± 0.05 | 0.98 ± 0.02 | 1.00 ± 0.05<br>1.00 ± 0.05 |
| 0925–0945 CST, 08-29-81 Labadie power plant | 0.87 ± 0.02 | 0.87 ± 0.06<br>0.87 ± 0.06 | 0.90 ± 0.02 | 0.90 ± 0.04<br>0.94 ± 0.05 | (Off scale) | 0.93 ± 0.07<br>0.92 ± 0.08 |
| 0658–0720 MST, 09-08-81 San Manuel smelter | 0.93 ± 0.02 | 0.94 ± 0.05<br>0.92 ± 0.05 | 0.92 ± 0.02 | 0.91 ± 0.03<br>0.89 ± 0.05 | 0.91 ± 0.02 | 0.93 ± 0.07<br>0.93 ± 0.07 |
| 0830–0840 MST, 09-08-81 San Manuel smelter | 0.89 ± 0.02 | 0.79 ± 0.04<br>0.91 ± 0.06 | 0.89 ± 0.02 | 0.72 ± 0.04<br>0.89 ± 0.06 | 0.94 ± 0.02 | 0.77 ± 0.02<br>0.93 ± 0.04 |
| 0845–0855 MST, 09-08-81 San Manuel smelter | 0.89 ± 0.02 | 0.87 ± 0.05<br>0.88 ± 0.04 | 0.91 ± 0.02 | 0.85 ± 0.04<br>0.88 ± 0.04 | 0.93 ± 0.02 | 0.92 ± 0.08<br>1.00 ± 0.05 |
| 0858–0908 MST, 09-08-81 San Manuel smelter | 0.94 ± 0.02 | 0.90 ± 0.06 | 0.94 ± 0.02 | 0.89 ± 0.05 | 0.96 ± 0.02 | 1.00 ± 0.05 |
| 0904–0929 MST, 09-09-81 San Manuel Smelter | 0.96 ± 0.02 | 0.91 ± 0.03<br>0.94 ± 0.06 | 0.95 ± 0.02 | 0.92 ± 0.03<br>0.95 ± 0.05 | 0.96 ± 0.02 | 0.93 ± 0.03<br>0.94 ± 0.06 |

the teleradiometer scan and another at the end. In one case (24 February 1981) an additional photograph was taken in the middle of the scan, and in another case (8 September 1981, 0858–0908 MST), no photograph was available for the end period of the scan.

The teleradiometric data are listed with a measurement uncertainty of 2 per cent (Bergstrom *et al.*, 1982). The sensitometric data are listed with an uncertainty that was determined for each scan, as described in section 2. The uncertainty in the sensitometric measurements of plume/sky radiance ratio averages 4 per cent and ranges from 1 to 9 per cent. It corresponds to an uncertainty in plume contrast of about 40 per cent and is therefore larger than the uncertainty estimated by Henry *et al.* (1981) that was on the order of 10 per cent for sky/target contrast. However, in the sky/target contrast measurements of Henry *et al.*, areas that include on the order of 100 pixels are used in calculating the contrast. This averaging of the pixel density over a large area allows one to decrease the uncertainty associated with the variation in pixel density resulting from the use of a small resolution. In this work, no averaging was used in the measurements of plume/sky radiance ratio since one seeks the maximum or minimum of the plume radiance along a vertical scan. In addition to the uncertainty due to the pixel resolution, estimating sky radiance at the same elevation angle as the measured plume radiance necessarily involves some uncertainty due to the interpolation between the sky radiances below and above the plume.

In all cases, the teleradiometric and sensitometric measurements agree within their range of uncertainty. Correlations between the two sets of data are presented in Table 2. In this correlation analysis, the sensitometric measurement of the plume/sky radiance ratio is taken as the average of the sensitometric measurements available. Correlation coefficients are of the order of 0.9. The regression lines closely approach the line of perfect agreement for the green and the red ranges.

The average absolute difference between the teleradiometric measurements and the sensitometric measurements corresponding to the photograph taken at the beginning of the teleradiometer scan is on the order of 4–5 per cent. The average absolute difference between the same teleradiometric measurements and the sensitometric measurements corresponding to the photograph taken at the end of the teleradiometer scan in of the order of 2–3 per cent. This discrepancy may be due to the fact that the actual teleradiometer measurement of the plume radiance occurs toward the end of the measurement period and is, therefore, closer in time to the second photograph.

From the results shown in Table 2, there appears to be little bias between the two techniques, and the average absolute difference is commensurate with the uncertainties associated with each measurement technique.

It is important to note that in four cases [20 February, 24 February, 24 August and 8 September (0830–0840 MST)] the variation in plume visibility due to changes in atmospheric conditions is larger than the difference between the two measurement techniques and larger than the measurement uncertainties. These cases suggest that the visual effects of atmospheric plumes may be highly nonstationary. Thus, it is difficult to accurately measure such plume visual effects by means of a teleradiometer operated manually since the measurement procedure takes on the order of 15 min. In such cases the sensitometric technique, despite its larger inherent uncertainty, appears to be more appropriate because it provides an instantaneous measure of the plume visual effects.

## 4. CONCLUSIONS

Teleradiometry and sensitometry have been used in the 1981 VISTTA field programs to measure the visual effects of power plant and smelter plumes.

Table 2. Correlations between teleradiometric and sensitometric measurements of plume visibility

| Parameter | Statistical data | | |
|---|---|---|---|
| | Blue range | Green range | Red range |
| Number of points | 10 | 10 | 9 |
| Correlation coefficient | 0.908 | 0.914 | 0.876 |
| Slope* | 1.238 | 1.015 | 0.966 |
| Intercept* | −0.225 | −0.034 | 0.031 |
| Average absolute difference† | 0.029 | 0.034 | 0.020 |
| Average bias‡ | 0.008 | 0.022 | −0.008 |

* Sensitometric data as a function of teleradiometric data.

† $\frac{1}{N}\sum_{i=1}^{N}\left|\frac{2(T_i - S_i)}{T_i + S_i}\right|$; $N$ = number of data pairs, $T_i$ = teleradiometric measurement, $S_i$ = sensitometric measurement.

‡ $\frac{1}{N}\sum_{i=1}^{N}\frac{2(T_i - S_i)}{T_i + S_i}$

Comparison of these two measurement techniques for a set of 10 cases typical of monitoring conditions shows good correlation, with correlation coefficients of the order of 0.9. The two techniques agree with each other within their range of experimental uncertainty, and no strong bias is apparent.

The uncertainty in the plume sky radiance ratio is about 4 per cent for sensitometry. It was estimated to be about 2 per cent for teleradiometry (Bergstrom *et al.*, 1982). Since the resolution of the view angle for the sensitometry technique is similar to that of a teleradiometer, it is likely that the film characteristics limit the accuracy of the sensitometric measurement.

The use of photographs for monitoring plume visibility appears to be a satisfactory technique, since it compares well with teleradiometry. The uncertainty associated with sensitometric measurements appears to be slightly larger than that of teleradiometric measurements; however, sensitometry offers the advantage of an instantaneous measurement. In contrast, a manual teleradiometer scan typically occurs over a 15-min period, and under certain atmospheric conditions, large variations in plume visual effects may occur during this period.

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